ABSTRACT

The aim of the article is to provide the reader with the basic concept of the transformer's heat utilization where a proposed technical solution anticipates the installation of an additional oil-water heat exchanger (ODWF) in the transformer's cooling system. An increase in the transformer's cooling capacity lowers the oil temperature and reduces the transformer's loss of life expectancy. In order to estimate the transformer's oil temperature profile, as well as the heat power potential at the water side of the ODWF cooler, a numerical investigation was performed on the 150 MVA 220 / 115 kV transformer unit which operates in Podlog substation in Slovenia.

KEYWORDS

transformer, cooling, forced cooling, heat loss, loss of life expectancy

Utilization of dissipated heat of power transformers

Simulation based analysis

1. Introduction

Heat disposal from large power transformers' units is achieved mainly through an oil-air cooler, in which the forced cooling prevails over the natural one. At higher loss densities, forced cooling solutions in the form of compact heat exchangers appear to be more economical and more suitable for installation. The cooling principle is common to forced, as well as to natural heat disposal. In general, the heat developed in the active part of a transformer, as well as in other constructional parts, is transferred to the internal cooling media, usually oil, and, further, through some kind of heat exchanger, delivered to an external coolant

The proposed conceptual solution for transformer's heat utilization encompasses the installation of an oil-water heat exchanger, ODWF, in addition to the existing main cooling system

which is either air or water, depending on the exchanger type. The types of cooling with the power transformers are defined by the Standards, here, we refer to the IEC 60076-2 Standard as shown in Table 1 [3].

The article deals only with the forced cooling process OF / OD, where the focus is put on an assessment of the heat loss that it is technically feasible to gain out of the transformer unit. A numerical consideration of a fully ODAF cooling transformer upgraded by the additional ODWF cooling system was conducted in the study. For this purpose, the parameters of a 150 MVA – 220 kV unit which operates in Podlog substation (Slovenia) were considered in the calculations. Several benefits were achieved by the installation of an additional ODWF cooler; firstly, the temperature conditions within the transformer changed in favour of its life extension. Another benefit is linked directly to the transformer's heat utilization, where the heat carried away to the water side of the ODWF compact cooler represents a potential energy source for the heat pump. The aim of the article is not only to estimate the potentially reusable transformer's heat power, but also to provide a reader with a basic theoretical and technical framework for the practical implementation of the proposed solution [4, 5].

2. Estimation of the potential usage of a transformer's heat

In order to estimate the utilization of transformers' heat loss it is valuable to be acquainted with the temperature conditions within the transformer unit, which depend on a transformer's losses. In general, the calculation of thermal profile of the oil and windings is, in the numerical sense, rather a comprehensive task, which requires construction details of the transformer's design, especially when the directed cooling of the windings (OD) is involved with it. Normally, the detailed construction parameters are not revealed by the manufacturers, thus, some simplifications and presumptions should be adopted in the numerical model [1, 3, 6]:

- Linear thermodynamic properties of the oil and the water are presumed for convenience
- The addiional ODWF cooler overtakes the same rate of transformer's losses at all operating conditions
- The transformer is operating near the nominal rated power and, therefore, the ODAF system is fully activated (all fan groups operate with full power)

Calculation of thermal profile of the oil and windings is a comprehensive task, which requires construction details of the transformer's design, especially for OD.. cooling

Table 1. Labelling the cooling systems with the power transformers

The coolant label	Meaning
O	Oil
A	Air
W	Water
Process of the coolant circulation	**Meaning**
N	Natural
F	Forced
D	Directed

Besides the heat utilization feasibility, the additional heat exchanger increases the transformer's cooling capacity amd extends its life expectancy

2.1 Assessment of the transformer's temperature profile

The case study was carried out on the operating transformer unit placed in the Podlog substation (Slovenia), and the transformer's data are collected in Table 2. The losses were evaluated at the nominal load and the central tap position. The following procedure will provide the reader with the basic calculation steps involved with the cooling system design (Table 2).

From the transformer's data, the total losses for which the cooling system should be designed can be determined by summing up the no-load and the short circuit losses, Eq. (1).

$$P_{tot} = P_k + P_0 \quad (1)$$

$$P_{tot} = 453{,}2 + 120{,}4 = 573{,}6\ kW$$

In the forced cooling principle, it is desired to know the mass flow Φ_{oil} and the volume flow Ψ_{oil} of the oil through the cooling system. The relations between the losses and the flows are given by Eqs. (2-3), where the temperature drop in the ODAF cooling system, as well as the cooler inlet oil temperature, are presumed to be $\Delta\vartheta'_{co}$ = 13°C and ϑ_{oic} = 83°C respectively, which somehow reflects real conditions within the heat exchanger. From the given temperatures follows the cooler outlet temperature $\Delta\vartheta'_{co}$ = 83°C - 13°C = 70°C and the mean cooler temperature

$$\vartheta_{ooc} = \frac{83°C + 70°C}{2} = 76{,}5°C,$$

at which the specific oil heat c_p = 2080 $Wskg^{-1}°C^{-1}$ and specific oil density ρ_{oil} = 849 kgm^{-3} are addressed. From Eq. (3) follows the estimated volume flow of the ODAF's oil pump when the transformer is cooled 100 % by the ODAF system. The characteristic oil temperatures within the transformer are given in Fig. (1) [4, 5].

$$\Phi_{oil} = \frac{P_{tot}}{c_p\,\Delta\vartheta_{co}} \quad (2)$$

$$\Psi_{oil} = \frac{\Phi_{oil}}{\rho_{oil}} \quad (3)$$

$$\Phi_{oil} = \frac{P_{tcel}}{c_p\,\Delta\vartheta_{co}} = \frac{573600}{208013} = 21{,}2\ kgs^{-1}$$

$$\Psi_{oil} = \frac{\Phi_{oil}}{\rho_{oil}} = \frac{21{,}2}{849} = 0{,}025\ m^3s^{-1}$$

$(25\ ls^{-1}, 90\ m^3h^{-1})$

Table 2. Large power transformer 150 MVA – 220 kV data placed in Podlog substation

Nominal data	Description	Value	Unit
Owner	ELES d.o.o.		
Location	Substation Podlog, Slovenia		
Manufacturer	Kolektor Etra, Slovenia		
Factory no.	63725		
Type	Regulating Transformer		
Nominal power S_n	Winding 1	150	MVA
	Winding 2	150	MVA
	Winding 3	50	MVA
Nominal voltage U_n	Winding 1	220	kV
	Winding 2	115	kV
	Winding 3	10.5	kV
Short circuit losses P_k	Winding 1-Winding 2 (@ 150 MVA)	453.2	kW
	Winding 1-Winding 3 (@ 50 MVA)	139.2	kW
	Winding 2-Winding 3 (@ 50 MVA)	119.4	kW
No-load losses P_0		120.4	kW
Type of cooling		ODAF	
Year of production		1986	

2.2 Transformer's heat utilization through the additional oil-water heat exchanger (ODWF)

By installing the compact water heat exchanger (ODWF) in addition to the existing ODAF cooling system, the cooling capacity increases and, consequently, the temperature conditions within the transformer are changed toward the lower values. The compact tube design ODWF unit can be placed on the remote construction and installed easily on the transformer tank through the oil filtration valves, as is shown in Fig. (2). Here, the subscripts ' and " refer to quantities pertaining to the ODWF and ODAF systems respectively [5].

The capacity of the additional ODWF cooler should be determined on the basis of heat demand of the individual substation facilities, but from the practical and economical aspect, especially when the transformer operates constantly near the nominal operating point, it is somehow sensible to install a cooler with slightly higher cooling capacity than one requires on the basis of heat

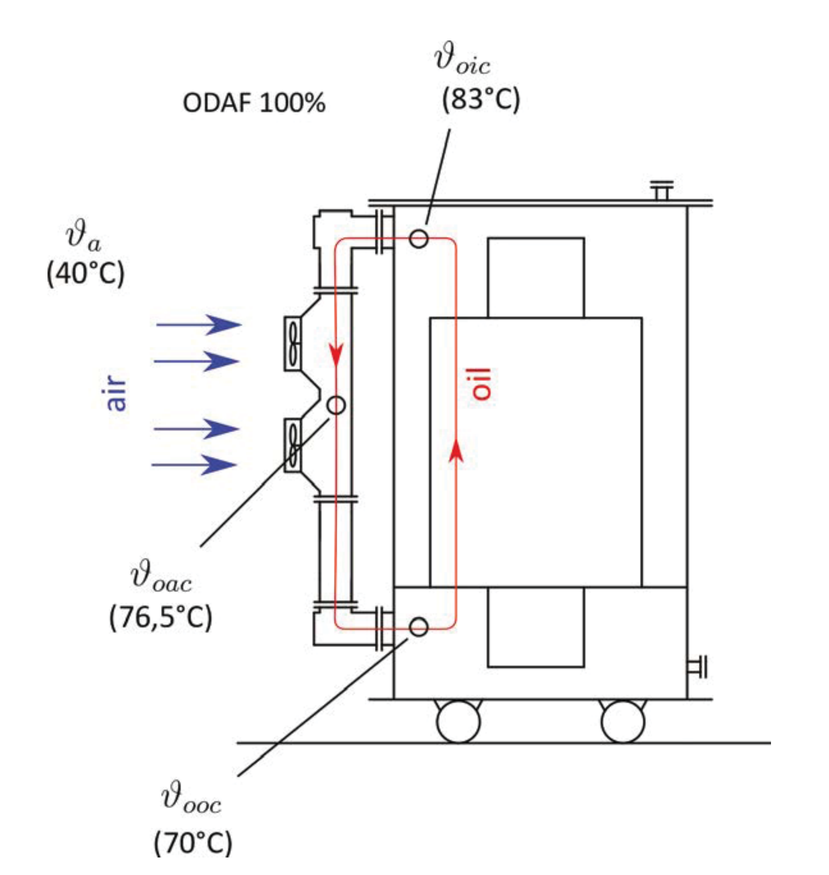

Figure 1. The assessment of the oil temperature profile pertaining to the 150 MVA / 220 kV (100 % ODAF cooled) transformer unit placed in Podlog substation, Slovenia

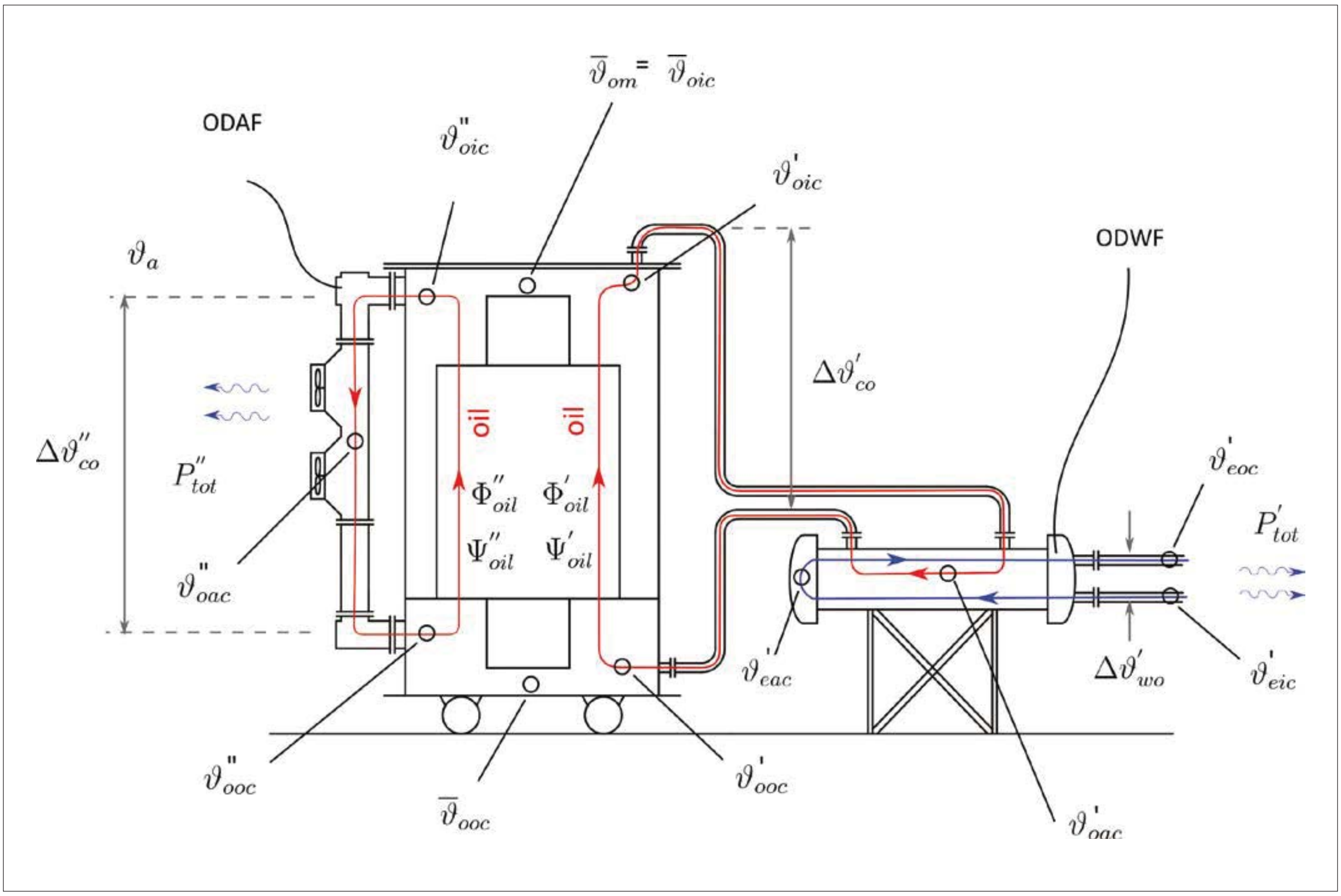

Figure 2. Transformer with the main ODAF 100 % and additionally installed ODWF 17,5 % heat exchanger

A compact tube design ODWF unit can be placed on the remote construction and installed easily to the transformer tank through the oil filtration valves

demand which allows the transformer to engage in an overload regime with reduced rate of its life loss expectancy. In the study, the cooler with the capacity of P'_c = 100 kW and a temperature drop of $\Delta\vartheta'_{co}$ = 8 K was considered in the calculations. Following the already adopted procedure using Eqs. (2-3), the oil flow rates (Φ'_{oil}, Ψ'_{oil}) of the additional cooler were obtained, Eqs. (2a-3a).

$$\Phi'_{oil} = \frac{P'_c}{c_p\,\Delta\vartheta'_{co}} = \frac{100000}{20808} = 6\ kgs^{-1} \quad (2a)$$

$$\Psi'_{oil} = \frac{\Phi'_{oil}}{\rho_{oil}} = \frac{6}{849} = \quad (3a)$$

$$0{,}007\ m^3h^{-1}\ (7\ ls^{-1}, 25\ m^3h^{-1})$$

The contribution of the ODWF cooler in the cooling process relieves the main ODAF system of 100 kW losses, thus, the temperature drop $\Delta\vartheta''_{co}$ through the ODAF system decreases, and at the unchanged oil flow rate (i.e. $\Phi_{oil} = \Phi''_{oil}$), the reduced temperature drop $\Delta\vartheta''_{co}$ is obtained as follows from Eq. (4).

$$\Delta\vartheta''_{co} = \frac{P_{tot} - P'_c}{c_p\,\Phi''_{oil}} = \frac{573600\text{-}100000}{208021{,}2} = 10{,}7K \quad (4)$$

The inlet ϑ''_{oic} and the outlet ϑ''_{oic} oil temperature related to the ODAF cooler is then, with respect to Eq. (4), calculated as is indicated by Eq. (5-6).

$$\vartheta''_{ooc} = \vartheta_{ooc} - \frac{\Delta\vartheta''_{co}}{2} = 70 - \frac{10{,}7}{2} = 64{,}7°C \quad (5)$$

$$\vartheta''_{oic} = \vartheta''_{ooc} + \Delta\vartheta''_{co} = 64{,}7 + 10{,}7 = 75{,}4°C \quad (6)$$

The same routine can be adopted to evaluate the inlet ϑ'_{oic} and the outlet ϑ'_{oic} oil temperature in the ODWF cooler, Eq. (5a-6a).

$$\vartheta'_{ooc} = \vartheta_{ooc} - \frac{\Delta\vartheta'_{co}}{2} = 70 - \frac{8}{2} = 66°C \quad (5a)$$

$$\vartheta'_{oic} = \vartheta'_{ooc} + \Delta\vartheta'_{co} = 66 + 8 = 74°C \quad (6a)$$

The tube type oil-water exchangers are regularly designed so that the temperature drop at the water side is somehow equal to the temperature drop at the oil side of the cooler [1, 7]. Considering the aforementioned performance of the cooler, the inlet and the outlet temperature of the water can be estimated. Presuming the water temperature entering the cooler to be ϑ'_{eic} = 25°C, then its outlet temperature is raised by the amount of the temperature drop $\Delta\vartheta'_{co}$ = 8°C to the value of ϑ'_{eoc} = 33°C. As a rule, the maximal temperature difference between the oil and water within the oil-water exchanger $\Delta\vartheta'_{o\text{-}e}$ should not exceed 60 K, value stated by the IEC Standard 60076-2. Therefore, special care should be devoted to the water temperature level that enters the exchanger.

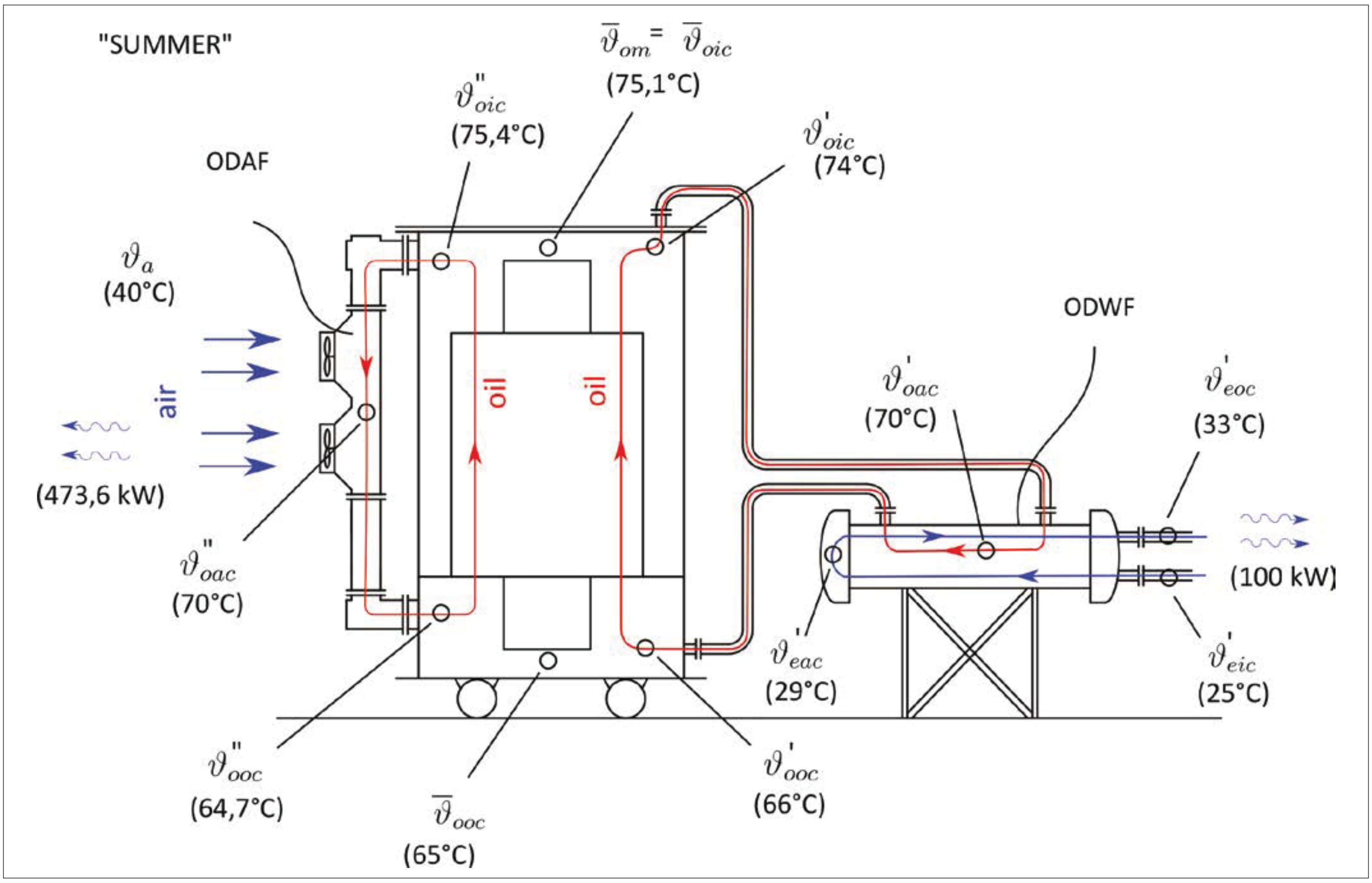

Figure 3. The assessment of the oil temperature profile within the transformer unit and the additional ODWF heat exchanger

Table 3. Total transformer's losses for cooling (P_{tot}) at the various loads, the division to the ODAF (P''_{tot}) and the ODWF (P'_{tot}) heat exchanger is given in addition

K_n	P_{tot} [kW]	P''_{tot} [kW]	P'_{tot} [kW]
0.8	410.5	338.6	71.8
0.9	487.5	402.2	85.3
1.0	573.6	473.2	100.4
1.1	668.8	551.7	117

In this case, the difference was 49 K, Eq. (7). The temperature conditions within the transformer cooled by the combined ODAF (100 %) and ODWF (17,5 %) system are given in Fig. (3) [3].

$$\Delta\vartheta'_{o\text{-}e} = \vartheta'_{oic} - \vartheta'_{eic} = 74\text{-}25 = 49\,K < 60\,K \quad (7)$$

The calculated temperature conditions shown in Fig. (3) hold for the nominally loaded transformer at an ambient temperature of $\vartheta_a = 40°C$. Regarding the fact that the transformer's load condition, as well as the ambient temperature change through the day, it is sensible to provide the estimation of the temperature conditions by varying the load and the ambient temperature.

When the possibility of the transformer's heat utilization through the ODWF cooler is concerned, the particularly interesting parameter for estimation is the difference between the outlet and the inlet temperatures at the water side of the cooler $\Delta\vartheta'_{eo}$.

The temperature conditions within the transformer are dependent mainly on the losses which are released as heat within the transformer's active parts. The losses consist of the steady state and the load-based part, where the first one pertains to the no-load losses P_0, while the other relates to the short circuit losses P_{kn}. The load losses obey the square law of a relative load K_n ($K_n = S/S_n$), as is indicated by Eq. (8). The nominal voltage at the transformer's terminal was adopted in the case study, thus the no-load losses were considered as constant. The total losses are given by Eq. (9).

$$P_k = P_{kn}K_n^2 \quad (8)$$

$$P_{tot} = P_{kn}K_n^2 + P_0 \quad (9)$$

The maximal temperature difference between the oil and water within the oil-water exchanger should not exceed 60 K, value stated by the IEC Standard 60076-2

The values of the losses overtaken by the individual cooling system are stated in Table 3. The division of the losses among the ODAF and the ODWF coolers was conducted by the presumption that 82,5 % of the total transformer's losses were passed to the main ODAF cooler (P''_{tot}), while the remaining 17,5 % is engulfed by the ODWF cooler (P'_{tot}) at all operating conditions Eqs. (10-11).

$$P''_{tot} = 0.825(P_{kn}K_n^2 + P_0) \quad (10)$$

$$P'_{tot} = 0.175\,(P_{kn}K_n^2 + P_0) \quad (11)$$

As long as the transformer is loaded near its rated load, an assessment of the oil temperature rise at the outlet of the cooler with respect to load can be given by a linear equation (12), where the factor Υ_{ooc} represents the ratio between the oil temperature rise entering the winding $\Delta\vartheta_{ooc}$ and losses that are carried away by the cooler P_{tot} at the nominal load conditions.

$$\Delta\vartheta_{ooc} = \Upsilon_{ooc}\,(P_{kn}K_n^2 + P_0), \quad (12)$$

$$\left(\Upsilon_{ooc} = \left.\frac{\Delta\vartheta_{ooc}}{P_{tot}}\right|_{K_n=1},\quad \Delta\vartheta_{ooc} = \vartheta_{ooc} - \vartheta_a\right)$$

In the combined ODAF – ODWF cooling system, and by the presumption of losses' division among the coolers (100 % ODAF+17,5 % ODWF), the factors Υ''_{ooc}, Υ'_{ooc} evaluated at the ambient temperature were $5{,}21 \cdot 10^{-5}\,°CW^{-1}$ and $26 \cdot 10^{-5}\,°CW^{-1}$, respectively.

The iterative approach in the temperatures' calculations should be employed, not only to encompass the load K_n and ambient temperature ϑ_a range, but also to consider the temperature dependence of the oil properties, i.e. the specific density $\rho = \rho(\vartheta)$ and specific heat $c_p = c_p\,(\vartheta)$, Eqs. (13-14) [1]. In the calculations, the average oil temperature in the cooler was used with Eqs. (13-14) [1].

$$\rho = -0.5814\vartheta + 893 \quad (13)$$

$$c_p = 4.2\vartheta + 1763 \quad (14)$$

For the safe and reliable operation, as well as for the life expectancy estimation of the transformer, it is essential to appreciate the top-oil temperature, thus, the inlet temperature in the heat exchangers (ODAF ϑ''_{oic} and ODWF ϑ'_{oic}) is presented graphically in Fig. (4). By performing the life expectancy analysis, one can show that, when the transformer is equipped with the additional 100 kW ODWF cooler, its life expectancy is extended by about two and a half times, and by this, the favourable effect on the transformer's insulation can be understood. For instance, the decrease of 10 % in the top-oil temperature means a reduction of the relative loss of life for about 60 %. In other words, this means that the loss of life for the transformer which operates 12 months with 10 % reduced top-oil temperature is equal to the one which operates 5 months with no reduction in the top-oil temperature.

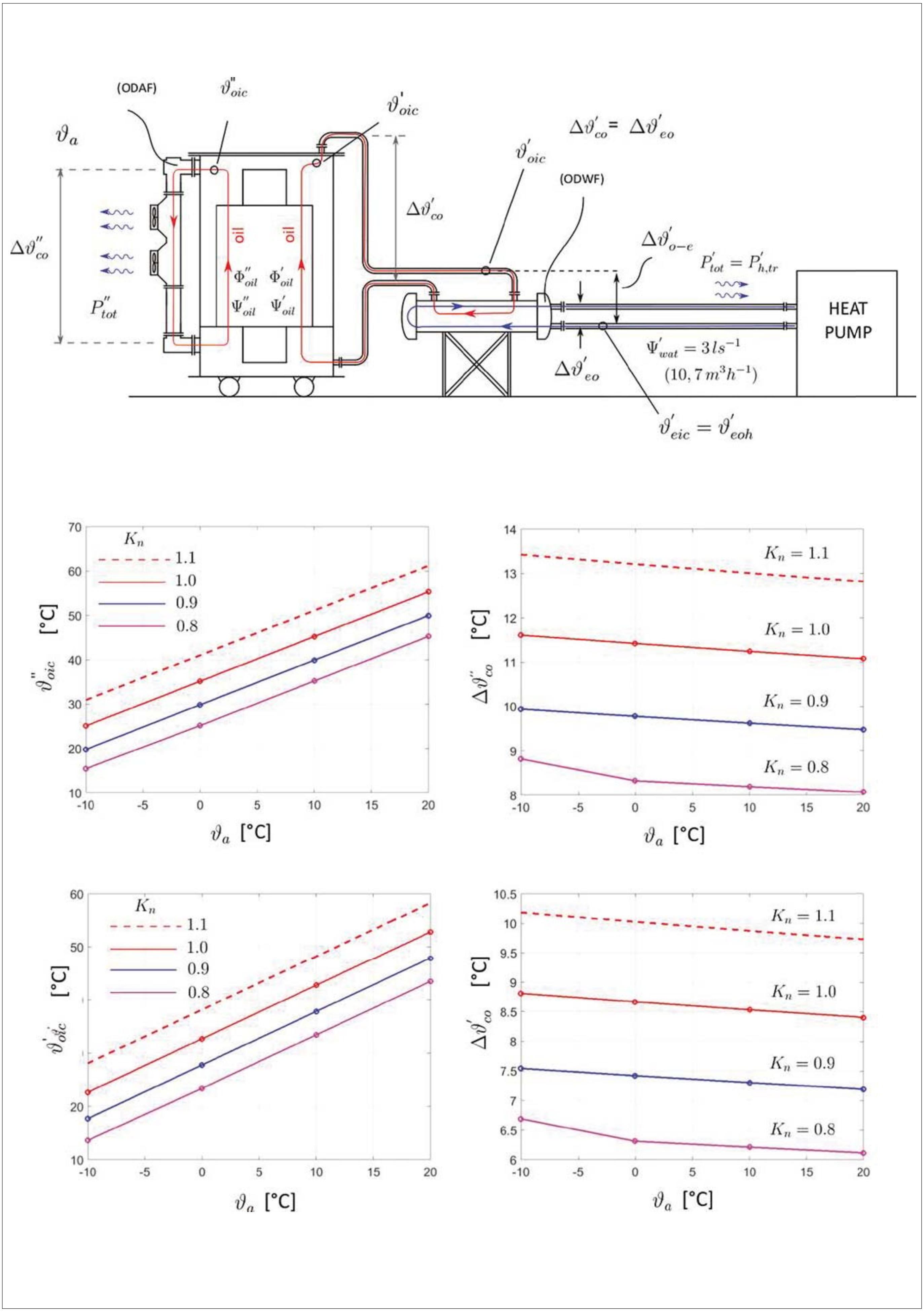

Figure 4. Typical oil temperatures which pertain to the main ODAF heat exchanger, calculated at the various ambient temperatures and load conditions

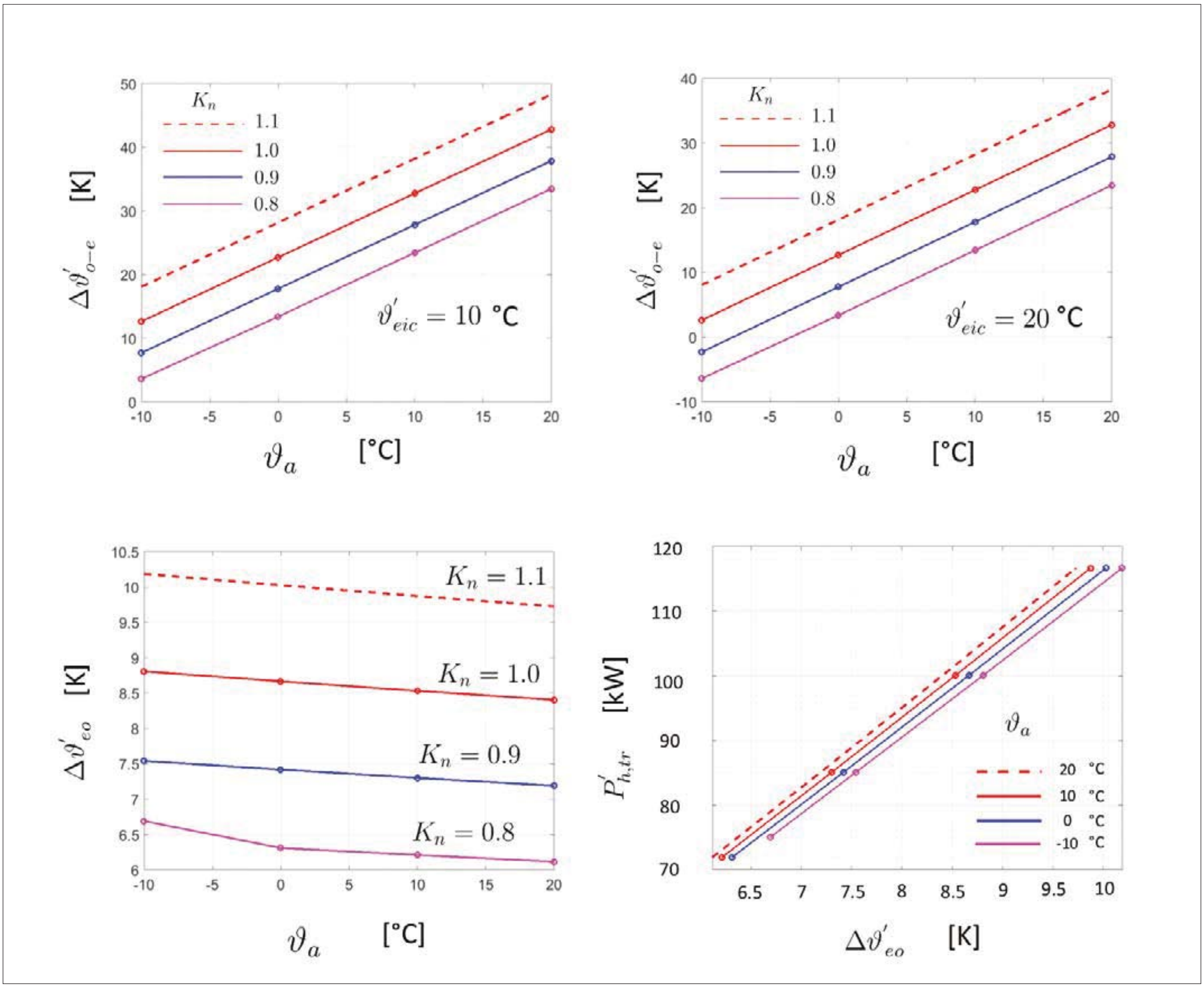

Figure 5: Typical oil temperatures and potentially obtainable heat power at the output of the additional ODWF heat exchanger, calculated at the various ambient temperatures and load conditions

The transformer's heat power potential can be estimated straightforwardly when the transformer operates near to its nominal rating power

When heat utilization is a subject of interest, the temperature difference at the water side of the ODWF cooler $\Delta\vartheta'_{eo}$ should be given too, as it is a key parameter, along with the conceptual solution of the transformer's heat employment as is shown in Fig. (4). Heating of the facility's building is planned according to the Standard Guidelines, where the heating system is designed by means of the desired thermal comfort in the building; for this reason, an estimated available heat power at the water side of the ODWF cooler $P'_{h,tr}$ with respect to the transformer's load and ambient temperature is also provided in Fig. (5) [1, 4, 5, 8].

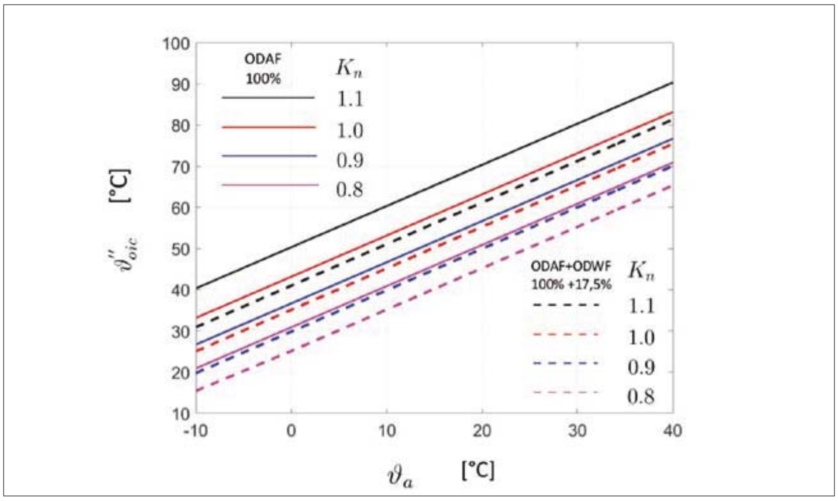

Figure 6: The top-oil temperature in the case when transformer operates with (dash lines) and without (solid lines) the additional ODWF 100 kW heat exchanger

To highlight the impact of the additional ODWF heat exchanger to the top oil temperature (ϑ''_{oic}), the additional figure, Figure 6, is provided for the case when the transformer operates with (dash lines) and without (solid lines) additional ODWF cooler.

Conclusion

The proposed conceptual solution towards the transformer's heat utilization encompasses the installation of the oil-water heat exchanger (ODWF) in addition to the existing main cooling system. The installation does not require any invasive intervention on the transformer's tank, because the ODWF heat exchanger is predicted to be placed on the remote console and joined with the transformer through the oil sample valves. Such approach not only enables the heat to be used in the heating process of the substations' facilities, but also increases the cooling capability of the transformer unit, which has a favourable effect regarding the transformer's life expectancy. The case study simulations showed that the transformer's heat power potential could be estimated straightforwardly when the transformer operates near to its nominal rating power, as well as

Table 4: Explanation of symbols appearing through the article

Description	Value
ϑ_{oic}, $\vartheta'_{oic\,(ODWF)}$, $\vartheta''_{oic\,(ODAF)}$	Cooler inlet oil temperature
ϑ_{ooc}, $\vartheta'_{ooc\,(ODWF)}$, $\vartheta''_{ooc\,(ODAF)}$	Cooler outlet oil temperature
ϑ_{oac}, $\vartheta'_{oac\,(ODWF)}$, $\vartheta''_{oac\,(ODAF)}$	Cooler average oil temperature
$\Delta\vartheta_{co}$, $\Delta\vartheta'_{co\,(ODWF)}$, $\Delta\vartheta''_{co\,(ODAF)}$	Difference of cooler inlet and outlet oil temperature
ϑ'_{eic}	Cooler inlet water temperature
ϑ'_{eoc}	Cooler outlet water temperature
ϑ'_{eac}	Cooler average water temperature
$\Delta\vartheta'_{eo}$	Difference of cooler inlet and outlet water temperature
$\Delta\vartheta'_{o\text{-}e}$	Difference between oil and water inlet temperature of the ODWF cooler
ϑ'_{eoh}	Output temperature of water from a heat pump
$\bar{\vartheta}_{om}$	Mean inlet cooler oil temperature
$\bar{\vartheta}_{ooc}$	Mean outlet cooler oil temperature
$\bar{\vartheta}_{oic}$	Mean inlet cooler oil temperature
ϑ_a	Ambient temperature
Φ_{oil}, $\Phi'_{oil\,(ODWF)}$, $\Phi''_{oil\,(ODAF)}$	Mass oil flow
Ψ_{oil}, $\Psi'_{oil\,(ODWF)}$, $\Psi''_{oil\,(ODAF)}$	Volume oil flow
Ψ'_{wat}	Volume water flow
P_k	Load losses
P_0	No-load losses
P_{tot}, $P'_{tot(ODWF)}$, $P''_{tot(ODAF)}$	Total losses carried out by cooler
$P'_{h,tr}$	Power delivered to a heat pump
Υ_{ooc}, $\Upsilon'_{ooc(ODWF)}$, $\Upsilon''_{ooc(ODAF)}$	Ratio between the oil temperature rise entering the winding and losses carried away by the cooler
K_n	Load factor
ρ	Specific oil density
c_p	Specific oil heat
S_n	Nominal power of a transformer
U_n	Nominal transformer voltage

that the top-oil temperature inside the transformer decreased by almost 10 % (7,6°C). To exploit the full capability of the additional heat exchanger, the one provided should have a sufficient amount of cooling water, which could be stored in the oil containment or special water pool. In practical applications, the efficiency of all elements involved in the cooling and heating process should be considered in detail, which yields that, in the real case, the transformer's heat utilization would somehow be lower than is obtained by the simulations.

Life expectancy analysis show that the life expectancy of a transformer equipped with an additional 100 kW ODWF cooler is extended by about two and a half times

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Authors

Mislav Trbusic received his B.Sc. in Electrical Engineering from the University of Ljubljana, Slovenia, in 2011. From 2011 to 2013 he worked at Kolektor Etra as a Design Engineer for Power Transformers. In 2014, he joined the Faculty of Electrical Engineering and Computer Science at the University of Maribor as an External Consultant. Currently, he is an Assistant and pursuing his Ph.D. in Electrical Engineering at the Faculty of Electrical Engineering and Computer Science. His research interests include transient phenomena in power transformers, high voltage devices, and magnetic liquids.

Robert Marusa received his B.Sc. degrees in electrical engineering and computer science from the University of Maribor in 1992 and 1998 respectively, an M.Sc. degree in public law from the National and European Studies Kranj in 2010, and a Ph.D. degree in electrical engineering from the University of Maribor in 2015. He is with Slovenia's Electric Power Transmission company (ELES), where he has been the Head of Maintenance in Podlog Substation since 1981. He is also an authorized Engineer with the Slovenian Chamber of Engineers. His interest is to pass over 30 years of experience to the younger generation of engineers and to teach them new methods and approaches in the field of maintenance. Dr. Marusa is the author of two patents and of more than 50 scientific as well as technical papers.

Jože Pihler was born in Ptuj, Slovenia, in 1955. He received his B.S., M.S., and PhD degrees in Electrical Engineering from the University of Maribor, Maribor, Slovenia, in 1978, 1991, and 1995, respectively. Since 1988, he has been a Researcher and Professor with the Faculty of Electrical Engineering and Computer Science, Department of Electrical Engineering, Institute for Power Systems, Maribor, Slovenia. His special fields of interest are Switching Devices and Switchgear. Prof. Pihler is a member of CIGRE and IEEE.

Anton Hamler received his B.Sc., M.Sc., and Ph.D. degrees in Electrical Engineering from the University of Maribor, Maribor, Slovenia, in 1983, 1989, and 1994, respectively. He has been with the Faculty of Electrical Engineering and Computer Science, University of Maribor, since 1983, and is currently a Professor of Electrical Engineering. His research interests include solving field problems by the Finite-Element Method, developing programme solutions for computer-aided design electromagnetic devices, and characterization of magnetic materials.